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BRANSON, J.

ESTIMATION OF BORON IMPURITIES IN GRAPHITE BY DANGER COEFFICIENT METHOD

JOHN J. BRANSON, JR.
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by

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Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

United States Naval Postgraduate School
Monterey, California

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ABSTRACT

Trace impurities of boron in reactor grade graphite cause a marked decrease in the quality of this material for reactor application. Accurate chemical analysis for boron at such levels is difficult and subject to considerable uncertainty. A method of estimating boron content by nondestructive testing utilizing the adverse effect of the impurity on the reactivity of a research reactor operating at a low power level is proposed. Such a method would include in boron content contributions due to some impurities, notably rare earths, not detected by chemical techniques. This investigation indicates that boron present in reactor grade graphite is of the order of 1.2 parts per million and greater than is shown by other methods. This boron content can be estimated with a significant precision of about 0.2 parts per million.

This project was done by the authors at the U. S. Naval Postgraduate School between August 1957 and January 1958. The AGN-201 research reactor was used on some 40 different occasions with approximately 160 hours of critical time. The authors wish to express their appreciation to Professor William W. Hawes who was present during all reactor operations due to licensing requirements. Other indebtedness is indicated under Acknowledgments.

TABLE OF CONTENTS

		Page
I	Introduction	1
II	Theory	3
III	Description of the AGN-201 Reactor	6
IV	Procedure	
	A. Measurement with Graphite	8
	B. Variation of Reactivity with Total Boron	10
	C. Geometry Effects	11
V	Results	13
VI	Discussion	15
VII	Conclusions	17
VIII	Acknowledgments	18
IX	References	19

LIST OF TABLES

TABLE		PAGE
I	Comparative Importance of Various Elements Present in a Typical Reactor Grade Graphite (AGOT)	20
II	Description of Graphite Samples Supplied by National Carbon Company	21
III	Relative Reactivities of Graphite Samples	22
IV	Change in Reactivity of Graphite Due to Changes in Weight	23
V	Description of Lucite Tubes	24
VI	Relative Reactivities of Water-Filled Tubes Contaminated with Boron	25
VII	Description of Polystyrene Cylinders	26
VIII	Estimation of Boron in Graphite Samples	27

LIST OF FIGURES

Figure Page

1. AGN-201 Inhour Equation 28
2. View of AGN-201 Reactor and Console 29
3. Equipment Used For Analysis of Boron in Graphite 30
4. Control Rod Calibration 31
5. Variation of Reactivity With Weight of Graphite Sample 32
6. Reactivity Effect of Boron in Water-Filled Tubes 33
7. Traverse of ½" Cylinder of Polystyrene Impregnated with Boron Through the Glory Hole Filled with Pure Polystyrene 34
8. Relative Change in Reactivity Due to Absorption as a Function of Sample Length 35
9. Reactivities of Graphite Samples 36
10. Estimation of Boron in Graphite Samples 37
11. Example of One Day's Runs with Water-Filled Tubes 38

1. INTRODUCTION

For a moderator a figure of merit commonly employed is the moderating ratio[1]. This is the ratio of the slowing down power of the substance to its absorption cross section. It is defined as $\xi \frac{\sigma_s}{\sigma_a}$ where σ_s and σ_a represent microscopic cross sections for scattering and absorption of neutrons, respectively[2]; ξ is the average logarithmic energy decrement. The worth of a moderator is greater the greater the value of the moderating ratio. High values of ξ and σ_s and a low value of σ_a are desired. With the exception of heavy water, pure graphite has the highest moderating ratio of those materials suitable for use as moderator. However, introduction of very small amounts of any material of high cross section for neutron absorption will reduce its effective moderating ratio significantly. The tolerable limit of boron is extremely low and much effort has been exerted to reduce boron content of graphite for reactor use as far as possible.

The chemical estimation of boron in insoluble materials is difficult and subject to substantial analytical errors when present in amounts many times that found in manufactured graphite[3]. Difficulties are increased as boron content is reduced. In reactor grades boron contents are certainly low enough that chemical analysis results may be quite unreliable.

It seemed likely that a nondestructive analytical method might be developed utilizing the strong dependence of reactivity $\delta K_{eff}/K_{eff}$ of a reactor at low power on the amount of boron introduced. The quantity K_{eff} has its conventional meaning and is the effective multiplication factor for a reactor

and is not much different from unity; δK_{eff} is $(K_{eff} - 1)$. At a low power level and $\delta K_{eff}/K_{eff}$ small, the neutron balance of the reactor is sensitive. A small change in neutron absorption or scattering is reflected in observable change in the value of the reactivity.

II. THEORY

During the graphitization process at 4500 - 5500 ^{o}F in the manufacture of artifical graphite, most impurities are volatilized. The boron content, on the other hand, seems to be accumulative and does not burn off[4]. Because the other impurities occur in more or less fixed amounts, have reasonably low thermal neutron cross sections, and have no outstanding resonance absorption peaks, their net effect could be regarded as common to all graphite made by the standard method. A base value of 3.27 millibarns (mb) for the absorption cross section of boron-free graphite may be computed. Assumed values of impurity content and corresponding contibutions to this absorption cross section are given in Table I. Any increase above this value may be attributed to boron. It should be pointed out that this procedure may lead to a high value for boron if certain rare earths are present. Very small traces of rare earths having very high neutron absorption cross sections[5] would be significant. In these amounts, independent estimation, or even detection, is beyond the scope of present methods.

A procedure based on the sensitivity of a reactor to neutron loss was developed with the first critical assembly[6]. As neutron absorbing impurities were particularly "dangerous" relative to the attainment of a chain reaction, the procedure came to be called the danger coefficient method of neutron absorption measurement. The method consisted essentially of placing a material with unknown nuclear properties in the center of the reactor and observing its effect on the reactivity.

As employed in the present study, the method utilizes either of two techniques. In the first, the reactor is made just critical with a reference material inserted. The test specimen is then substituted and the control rods repositioned to compensate for the change in neutron economy. Alternately, the reactor is adjusted for a convenient positive stable period with either a reference or a test specimen and the periods are determined with no change in control rod position. In either case, the reactivity ρ is given by the expression sometimes referred to as the inhour equation:

$$\rho = \frac{\delta K_{eff}}{K_{eff}} = \frac{\ell}{T K_{eff}} + \gamma \sum_{i=1}^{6} \frac{A B_i}{1 + \frac{0.693 T}{T_{1/2\,i}}}$$

where:

ℓ = mean lifetime of thermal neutrons

T = stable reactor period

K_{eff} = effective multiplication

γ = mean effectiveness of delayed neutrons

A = the delayed fraction of total fission neutrons

B_i = fraction of delayed neutrons in the i th group

$T_{1/2\,i}$ = half life of the i th group precursor

The values used for the above quantities and the six delayed neutron groups are listed in Appendix A. A logarithmic plot of the equation is also shown in Appendix A. A linear plot is shown in Figure 1. The quantity actually observed is not the period T but the monitored neutron flux. The value of T is readily obtained from the relation:

$$\phi = \phi_0 e^{t/T}$$

in which ϕ is the flux at time t and ϕ_0 is the initial flux at t = 0.

III. DESCRIPTION OF THE AGN-201 REACTOR

The Aerojet-General Nucleonics Model 201 research reactor has been described[7]. The reactor operates at a maximum power of 0.1 watt and a flux of 4.5×10^6 neutrons/cm^2 sec and was used at this level for the present investigation. Figure 2 indicates the general arrangement of the reactor and console. It should be noted that the "glory hole" consists of an aluminum tube of slightly less than one inch inside diameter passing directly through the center of the reactor. For symmetry and minimum disturbance of neutron flux, the portion of the glory hole not containing a test specimen is filled with a holder containing plugs to match the normal reflector and shielding. The sample holder is displayed with other equipment in Figure 3. The core is a homogeneous mixture of UO_2, 20% enriched in U-235, in polyethylene in the form of a vertical right cylinder ten inches in diameter and 9½ inches high.

The thermal power level of the reactor is indicated at the control console by a Keithly micro-microammeter, model 410, reading the output of a BF_3 ionization chamber located inside the water shield just outside the lead shield. The output of the micro-microammeter was fed to a Varian strip recorder, model G-10, through a voltage divider adjusted to give seventy percent of full scale deflection (20 - 90) of the recorder over the range of flux desired, namely from 1×10^6 to 4.5×10^6 neutrons/cm^2 sec.

Control rod positions are indicated at the console to a precision of 0.01 cm. It was found experimentally that reset accuracy corresponded closely to the indicated precision yielding an

uncertainty in change of reactivity of about 2×10^{-6} (hereafter referred to as $2\mu\rho$) in the most reliable range. One fine and one coarse control rod are provided. They were intercompared and the worth as excess reactivity per centimeter was determined for the fine control rod over its full span of travel and for the upper portion of the coarse rod's travel[8]. Resulting calibration curves are shown in Figure 4.*

---

*The ratio of the slopes (3.85:1) agrees exactly with the ratio of fuel loading of the coarse and fine control rods[9] which indicates a satisfactory calibration.

IV. PROCEDURE

A. Measurements with Graphite

Graphite samples were furnished by the National Carbon Co. As described in Table II, they were solid cylinders six inches long, 7/8 inch in diameter, having machined surfaces. Prior to shipment special precautions had been taken to avoid contamination in preparation and packing of the specimens. Upon receipt they were used without further preparation except for wrapping with several layers of cellophane*, which served to protect against contamination and also against any abrasion during placement in and removal from the reactor. The wrapped samples are pictured in Figure 3.

Relative changes in reactivity for all specimens were determined by positioning of control rods and adjustment to $K_{eff}=1$. In these measurements the fine control rod only was moved and changes were effected within the linear range of the calibration curve. It was found that considerable time was usually necessary for sufficiently close adjustment and that drift in stability tended to introduce error. Results are tabulated in the second column of Table III.

The graphite samples were rerun using the period measurement technique. With one graphite sample in place enough fine control rod was added to give a period of 250 - 300 seconds. When the reactor power increased to its designed limit of 0.1 watt, the sample holders were removed. The loss of moderating mate-

---

*Initially, samples were wrapped in Saran (vinylidene chloride) but its chlorine content caused a large decrease in reactivity. Several other wrappings, namely, cellophane, waxed paper, aluminum foil, and polyethylene film, were evaluated and all showed nearly zero effect on reactivity.

rial caused a power decrease. At a preselected level the sample holders were reinserted, with the period of the resulting power rise being the measured quantity.

By use of this technique a cycle was completed in approximately ten minutes. Seven points representing the last three and one half minutes were read from the recorder and replotted to give:

$$\ln \phi - \ln \phi_0 = \frac{t}{T} + C$$

from which the period T is readily obtained. Premature readings taken before the delayed neutron effect reached equilibrium could be detected by a curve in an otherwise straight line. Electrical transients introduced during a slope determination could be detected by a step in the straight line.

By running one graphite sample (GBF-1) every few runs a true picture of the temperature drift could be obtained. Because the control rods did not move during the slope determinations it was believed a more constant flux distribution existed in the reactor core. The values of reactivity calculated are given in column 3 of Table III.

In the above series slight disarrangements of the shield and reflector plugs in the sample holders account for some scatter in the observed reactivity. A coil spring and wooden dowel backing were added to the sample holder contents as seen in Figure 3. This was sufficient to insure constant placement of the plugs despite any jar in handling. With the improved sample holders another set of period measurements was made and the data

are recorded in column 4 of Table III. They were believed the most accurate.

Since the effect of the graphite would be proportional to the number of atoms, the effect of changing weight with a constant composition was of interest. A piece of standard electrode graphite was cut to the size of the other samples. This sample was then weighed, checked for reactivity in the reactor, turned down a few thousands of an inch, reweighed, rechecked in the reactor, etc. Four determinations of reactivity were made as indicated in Table IV. These data include the effect of boron content. However, since this is constant, a sufficient approximation can be made for correction, as is shown later.

B. Variation of Reactivity with Total Boron

Four similar lucite tubes were constructed and are illustrated in Figure 3. Some characteristics are tabulated in Table V. The size corresponds to the full in core dimensions fo the glory hole. Water was introduced to essentially fill and the tubes sealed. The water had been purified by distillation and slow passage through a mixed bed of ion exchange resins*. Intercomparisons following the same procedure outlined under the third and last set of graphite measurements showed no significant difference in reactivity among the four tubes. They were considered identical for this purpose and no correction was neces-

---

*Cation exchange resin, 100-200 mesh, hydrogen form, BIO-RAD Laboratories, control no. 3604 21B 166.

Anion exchange resin, 100-200 mesh, chloride form, BIO-RAD Laboratories, control no. 3604 8B 144.

sary for the minor weight differences shown in Table V.

A standard solution of boric acid was added to each of three tubes in increments of 0.100 milliliters of solution or 103.5 μg of boron. Additions were made using a micropipette and a constant volume of solution was maintained. Reactivities of the boron containing tubes and the pure tube were compared to determine the effect of dissolved boron. It was assumed that the effect of the uniformly distributed boron in graphite would be the same. The results were recorded in Table VI and plotted in Figure 6.

Figure 6 clearly indicates that no self shielding effect was observed below 1035 μg of boron. The effect of uniformly distributed boron in the central nine inches of the core is -0.055 μρ/μg of B.

C. Geometry Effects

Twenty cylinders of ½ inch length and sample holder diameter were molded from finely powdered polystyrene.* They are shown in Figure 3 and described in Table VII. An additional cylinder was molded from the same polystyrene after it had been mechanically mixed for three days with finely powdered boric oxide glass. The boric oxide glass was prepared by fusion of boric acid at 500°C and grinding in an agate mortar.

Position traverse measurements were made with the boron filled cylinder through the entire core by successively replacing pure cylinders numbers one through twenty. The resulting traverse of the core diameter is shown in Figure 7.

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*Crystal polystyrene, 3X beads, KOPPERS Co., Inc. sample no. C5K-5084

From graphical integration under the curve of Figure 7 the relative effect on the reactor of distributed boron as a function of position may be determined. This was plotted as a normalized curve in Figure 8. A comparison of the values for six and nine inch lengths in Figure 8 indicated the effect of the boron was multiplied by 1.2 for the shorter length. Applying this correction to the value for specific reactivity change obtained with boric acid solutions a new value of -0.066 $\mu\rho/\mu g$ of B is found.

V. RESULTS

It was shown that the graphite measured at varying masses exhibited behavior similar to that of the sample of electrode graphite, as would be expected. For purpose of correction for its boron content the assumption that the two had identical boron contents was justified. The correction was not large and unless the assumption is greatly in error the resulting value for dependence of reactivity on graphite mass should be substantially correct. The absorption cross section given for electrode graphite was 5.0 mb. Taking this value for use as a correction the slope becomes +4.80 $\mu\rho/g$ for boron-free graphite.

From the assembled data it was then possible to compute boron values for the several samples. In Table 1 boron-free graphite was assigned a value of 3.27 mb for σ_a and this value should increase by 0.84 mb for each ppm of boron. As previously indicated there is evidence that the data from the last column of Table III is the most accurate. These values were plotted in Figures 9 and 10. Several considerations led to the conclusion that the σ_a value of 4.0 mb of sample GBF was probably the most reliable. Therefore GBF would have 0.73 mb due to boron. This would represent 0.87 ppm by Table 1 values. This in turn represented 89.5 μg of boron at the weight of GBF-1 and 88.1 μg at the weight of GBF-2. That much boron in a six inch length by -0.066 $\mu\rho/\mu g$ of boron would represent -5.9 $\mu\rho$ in GBF-1 and -5.8 $\mu\rho$ in GBF-2.

In Figure 9 and its expanded plot of Figure 10 the reference base was constructed to yield these values for the GBF specimens.

The corrected slope for boron-free graphite of +4.80 $\mu\rho/g$ of carbon was drawn through said points. The boron content of other graphites may then be calculated. These values are listed in Table VIII. Briefly, it was found that AGOT contains about 1.2 ppm of boron and for AGR one sample contains 2.6 ppm while the other has only 0.8 ppm.

VI. DISCUSSION

The absolute accuracy obtained is dependent on both the experimental scatter of measurements and the validity of assumptions leading to the base values.

In all measurements a slow drift in reactivity was observed. The drift was not constant or predictable but was generally downward after initial stabilization. The behavior suggested a temperature variation.[10] The temperature coefficient of the reactor was about -275 $\mu\rho/^\circ C$. It may be shown that the heat produced by the reactor operating at 0.1 watt thermal power is inadequate to account for the observed drift. However, some connection with changes in ambient air temperature and radiant energy was found. For example, the drift was greatest on bright days and at a time of day when changes in solar heating were most pronounced. This may well be the primary cause for the drift or at least contribute importantly. The drift made necessary the concurrent running of a standard. In early measurements a standard was run alternately with a specimen but this frequency appeared unnecessary and in later experiments was reduced to one in every two or three runs.

As an illustration of the data treatment techniques used, the one point representing the reactivity change caused by 931.5 μg of boron in aqueous solution may be examined in more detail. Figure 11 shows the reactivities determined in tubes one through four plotted against time. Tube one contained pure water while the others were filled with solutions of the above concentration. The drift was assumed to be linear and a straight line was fitted to the more numerous points of tubes two through four by the method of least squares.[12] The standard

deviation of such a line was calculated as 1.0 $\mu\rho$. The drift was assumed the same for the number one tube and a parallel line was fitted to those points. The standard deviation of this line was 1.8 $\mu\rho$ for a total standard deviation of 2.8 $\mu\rho$ The difference between the lines then corresponded to 51±2.8 $\mu\rho$, as reported. Obviously, the total standard deviation could be reduced by more frequent observation of the standard.

The best values obtained for graphite show a probable error of about 1.4 $\mu\rho$. This represented about 20 μg total boron for the sample or 0.2 ppm. As seen in Table VIII the final result indicated different boron content in some of the sample pairs considered. An examination of the AGR sample pair indicated that AGR-1 contained more boron than AGR-2. The difference is more than can be accounted for by experimental error and it must be concluded the difference is real. Results on pairs of other samples which were believed to be cut from the same block agree within the probable error of the determinations. The assumptions involved in base value estimation affect the absolute accuracy but not the relative values for the various graphite samples.

Results with sample 2-4 were clearly inconsistent. Sample 2-4 exhibited an increased reactivity considerably beyond that attributable to its mass. From the magnitude of the increase it seemed evident that some neutron scatterer other than carbon was present. This sample was described as impregnated. If the sample was impregnated with pitch which contains hydrogen and the hydrogen was not removed completely during the graphitization, this could account for the increased reactivity.

VII. CONCLUSIONS

Boron content can be estimated by the use of a low power research reactor. The boron content reported would include the effects due to high cross section rare earths if present.

The present method permits a determination about every ten minutes of reactor time with several determinations necessary to achieve satisfactory precision at boron levels of interest. A sensitivity of about 0.2 ppm of boron has been obtained.

VIII. ACKNOWLEDGMENTS

The authors wish to express their appreciation for the assistance and encouragement given them by Professor William W. Hawes and Professor John R. Clark of the U. S. Naval Postgraduate School in this investigation. The authors are also indebted to National Carbon Corporation for the generous contribution of the graphite samples tested. Appreciation is expressed to Aerojet-General Nucleonics and particularly Dr. G. A. Linenberger for helpful information concerning the AGN-201 reactor.

IX. REFERENCES

1. S. Glasstone and M. C. Edlund, The Elements of Nuclear Reactor Theory, D. Van Nostrand Co., 1955.

2. D. J. Hughes and J. A. Harvey, Neutron Cross Sections, Vol. 5 of Selected Reference Material, U. S. Atomic Energy Program, Associated Universities, Inc., 1955.

3. W. F. Hillebrand and G. E. F. Lundell, Applied Inorganic Analysis, John Wiley and Sons, Inc., 1953, Chapt. 49.

4. J. J. Newbert, J. Royal, and A. R. Van Dy Ken, The Structure and Properties of Artificial and Natural Graphite, ANL-5524, February 1956.

5. L. M. Currie, et al, The Production and Properties of Graphite for Reactors, National Carbon, 1955.

6. H. L. Anderson, et al, Method for Measuring Neutron-Absorption Cross Sections by the Effect on the Reactivity of a Chain-Reacting Pile, Phys. Rev. 72, 16, July 1947.

7. A. T. Biehl, et al, Compact Low-Cost Reactor Emphasizes Safety, Nucleonics, 14, 100-103, Sept. 1956.

8. Aerojet-General Nucleonics Staff, Educational Experiments Utilizing the AGN-201 Nuclear Reactor, AGN Report No. 16, Jan. 1957, Exp. No. 3.

9. AEC Form 388, SS Material Transfer Form-License Material, For Enriched Uranium Shipped from Aerojet-General Nucleonics to the U. S. Naval Postgraduate School on April 29, 1957.

10. D. J. Hughes, Pile Neutron Research, Addison-Wesley Publishing Co., 1953.

11. M. M. Harvey, et al, A Summary of Experimental Investigations of the AGN-201, Aerojet-General Nucleonics Report No. 22, June 1957.

12. J. B. Scarborough, Numerical Mathematical Analysis, Johns Hopkins Press, 1930.

TABLE I

COMPARATIVE IMPORTANCE OF VARIOUS ELEMENTS PRESENT IN A TYPICAL REACTOR GRADE GRAPHITE (AGOT)

ELEMENT	TYPICAL ANALYSIS (ppm)	ATOMIC WEIGHT	σ_a (BARNS)	σ_s (BARNS)	σ_a^* (BARNS)	σ_s^* (BARNS)
Carbon	10^6	12.01	0.0032	4.8	$3.2\mathrm{x}10^{-3}$	4.8
Calcium	185	40.08	0.43	9	$0.022\mathrm{x}10^{-3}$	$5.5\mathrm{x}10^{-3}$
Titanium	9	47.90	5.6	4	$0.013\mathrm{x}10^{-3}$	$.36\mathrm{x}10^{-3}$
Vanadium	18	50.95	5.1	5	$0.022\mathrm{x}10^{-3}$	$0.8\mathrm{x}10^{-3}$
Iron	32	55.85	2.53	11	$0.017\mathrm{x}10^{-3}$	$3.5\mathrm{x}10^{-3}$
Total (without Boron)	10^6				$3.27\mathrm{x}10^{-3}$	4.8
Boron	1	10.82	755	4	$0.84\mathrm{x}10^{-3}$	$4.4\mathrm{x}10^{-6}$
Total (with Boron)	10^6				$4.11\mathrm{x}10^{-3}$	4.8

NOTES: (1) It can be seen that one part per million of Boron increases the graphites absorption cross section for thermal neutrons by about 27% while the same amount of Boron has no effect on the scattering cross section.

(2) Cross section values are from Reference 1.

SYMBOLS:

σ_a = thermal neutron absorption cross section (barns)

σ_s = " " scattering " " "

σ_a^* = weighted effect on $\sigma_a = \sigma_a \frac{\text{ATOMIC WT. CARBON}}{\text{ATOMIC WT ELEMENT}} \times \frac{\text{ppm ELEMENT}}{\text{ppm CARBON}}$

σ_s^* = " " " $\sigma_s = \sigma_s$ " " x "

TABLE II

DESCRIPTION OF GRAPHITE SAMPLES SUPPLIED BY NATIONAL CARBON COMPANY

SAMPLE	BORON CONTENT*	CROSS SECTION*	DESCRIPTION
AGOT	not reported	about 4.9 mb.	Standard reactor graphite
GBF	not reported	2.0 mb.	Gas baked and purified coke
AGR	0.6 ppm	5 mb	Standard electrode graphite
2-4	not reported	22.6 mb	Impregnated graphite

DIMENSIONS AND WEIGHTS

All samples six inches long and 7/8 in. diameter, except for 2-4, whose lengths were 3 in. Each six inch sample and pairs of three inch samples were wrapped in 6"x7" sheets of cellophane before weighing, and a correction was made for the weight of wrapping.

SAMPLE NUMBER	NET WEIGHT (g)
AGR-1	92.6193
AGR-2	92.4405
AGOT-1	97.5709
AGOT-2	97.1468
GBF-1	102.2789
GBF-2	101.3239
2-4 (1+2)	110.9061
2-4 (3+4)	111.2804

*Analysis and cross sections reported by National Carbon Co.

TABLE III

RELATIVE REACTIVITIES OF GRAPHITE SAMPLES

SAMPLE	REACTIVITY By Rod Position	By Slopes (First)	By Slopes (Final)
AGR-1	484	485 ± 1.9	485 ± 1.9
AGR-2	483	470 ± 11.6	495 ± 3.3
AGOT-1	516	503 ± 5.7	516 ± 2.4
AGOT-2	511	514 ± 5.7	516 ± 2.3
GBF-1	541	541 ± 1.1	541 ± 2.2
GBF-2	536	532 ± 3.8	537 ± 2.2
(2-4)- 1 + 2	680	683 ± 5.0	693 ± 2.1
(2-4)- 3 + 4	682	684 ± 6.8	689 ± 2.9
Polyethylene	938	-	-
Air Volume (void)	0	0	0

NOTE: The reactivities observed by period measurements used varying base points. After observation they were all referred to a common base point (air volume or void=0.) The deviations indicated are for the difference measurement and not for the total reactivity.

TABLE IV

CHANGE IN REACTIVITY OF GRAPHITE DUE TO CHANGES IN WEIGHT

SAMPLE	LENGTH (in)	DIAMETER (in)	WEIGHT (g)	REACTIVITY ($\mu\rho$)
X-1	6	0.875	93.64	497 ± 3.6
X-2	6	0.835	86.16	455 ± 3.4
X-3	6	0.800	80.70	436 ± 2.1
X-4	6	0.705	60.90	343 ± 3.2

TABLE V

DESCRIPTION OF LUCITE TUBES

DIMENSIONS

LENGHT:	overall	10 in.
	water space	9 in.
DIAMETER:	inside	3/4 in.
	outside	7/8 in.

WEIGHTS

Tube number	Empty weight (g.)	Filled weight (g.)	Weight water (g.)
1	44.1320	107.2034	63.0714
2	43.9630	107.1410	63.1780
3	44.2141	107.1784	62.9643
4	44.1486	107.2093	63.0607

DETAIL OF TUBE ENDS

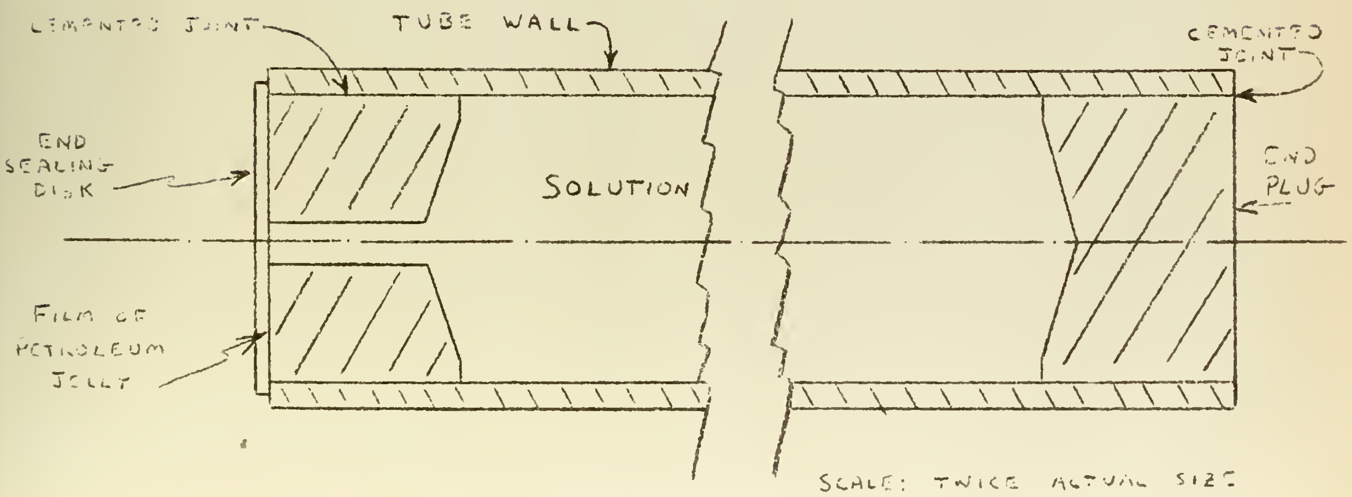


TABLE VI

RELATIVE REACTIVITIES OF WATER-FILLED TUBES CONTAINING BORON

LOADING		REACTIVITY
VOLUME OF SOLUTION (ml)	WEIGHT OF BORON (μg)	(μρ)
100	103.5	6.0 ± 2.0
200	207.0	11.5 ± 2.8
300	310.5	19.0 ± 2.3
400	414.0	19.5 ± 3.0
500	517.5	31.0 ± 3.6
600	621.0	34.0 ± 2.5
700	724.5	37.0 ± 3.0
800	828.0	44.0 ± 3.6
900	931.5	51.0 ± 2.8
1000	1035.0	57.0 ± 3.6

TABLE VII

DESCRIPTION OF POLYSTYRENE CYLINDERS

DIMENSIONS: All cylinders were one half inch long and 0.8 inch in diameter.

WEIGHTS:

PURE CYLINDERS

No.	wt. (g)
1	4.399
2	4.340
3	4.260
4	4.514
5	4.309
6	4.222
7	4.346
8	4.307
9	4.312
10	4.360
11	4.379
12	4.186
13	4.095
14	4.406
15	4.333
16	4.333
17	4.367
18	4.493
19	4.288
20	4.237

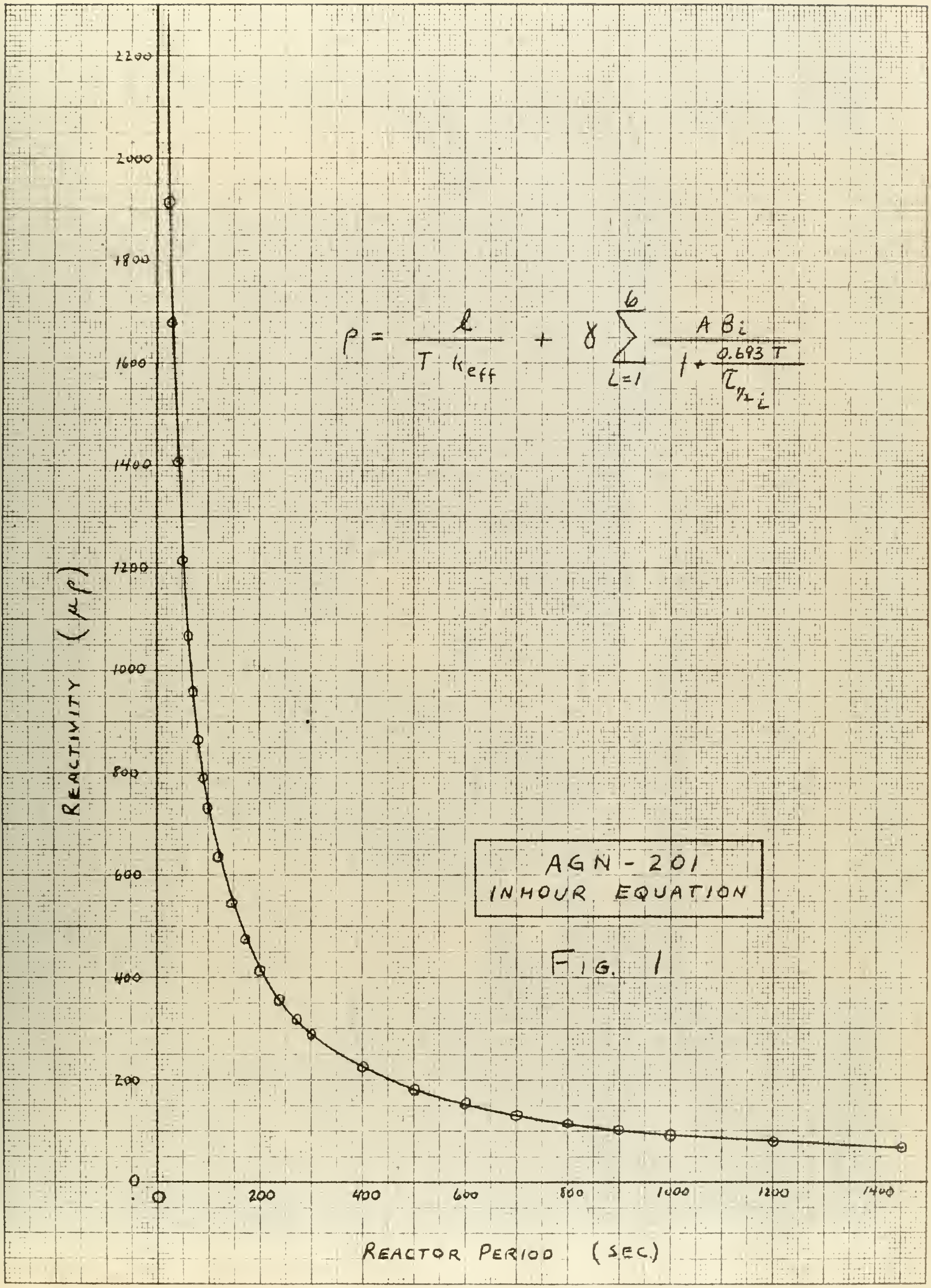
BORON IMPREGNATED CYLINDER

No.	wt. (g)
B-1	4.1438

TABLE VIII

ESTIMATION OF BORON IN GRAPHITE SAMPLES

SAMPLE	REACTIVITY DUE TO BORON $(\mu\rho)$	BORON CONTENT (μg)	BORON CONTENT (ppm)
GBF-1	5.9 ± 2.2	89.1 ± 33.4	0.87 ± 0.33
GBF-2	5.8 ± 2.2	88.1 ± 33.4	0.87 ± 0.33
AGOT-1	8.6 ± 2.4	130.0 ± 36.4	1.33 ± 0.37
AGOT-2	6.5 ± 2.3	98.5 ± 34.9	1.01 ± 0.36
AGR-1	15.8 ± 1.9	239.0 ± 28.8	2.58 ± 0.31
AGR-2	5.0 ± 3.3	75.8 ± 50.0	0.82 ± 0.36



$$\rho = \frac{\ell}{T\,k_{eff}} + \gamma \sum_{i=1}^{6} \frac{A\beta_i}{1 + \frac{0.693\,T}{\tau_{1/2_i}}}$$

AGN - 201
INHOUR EQUATION

FIG. 1

Fig. 1

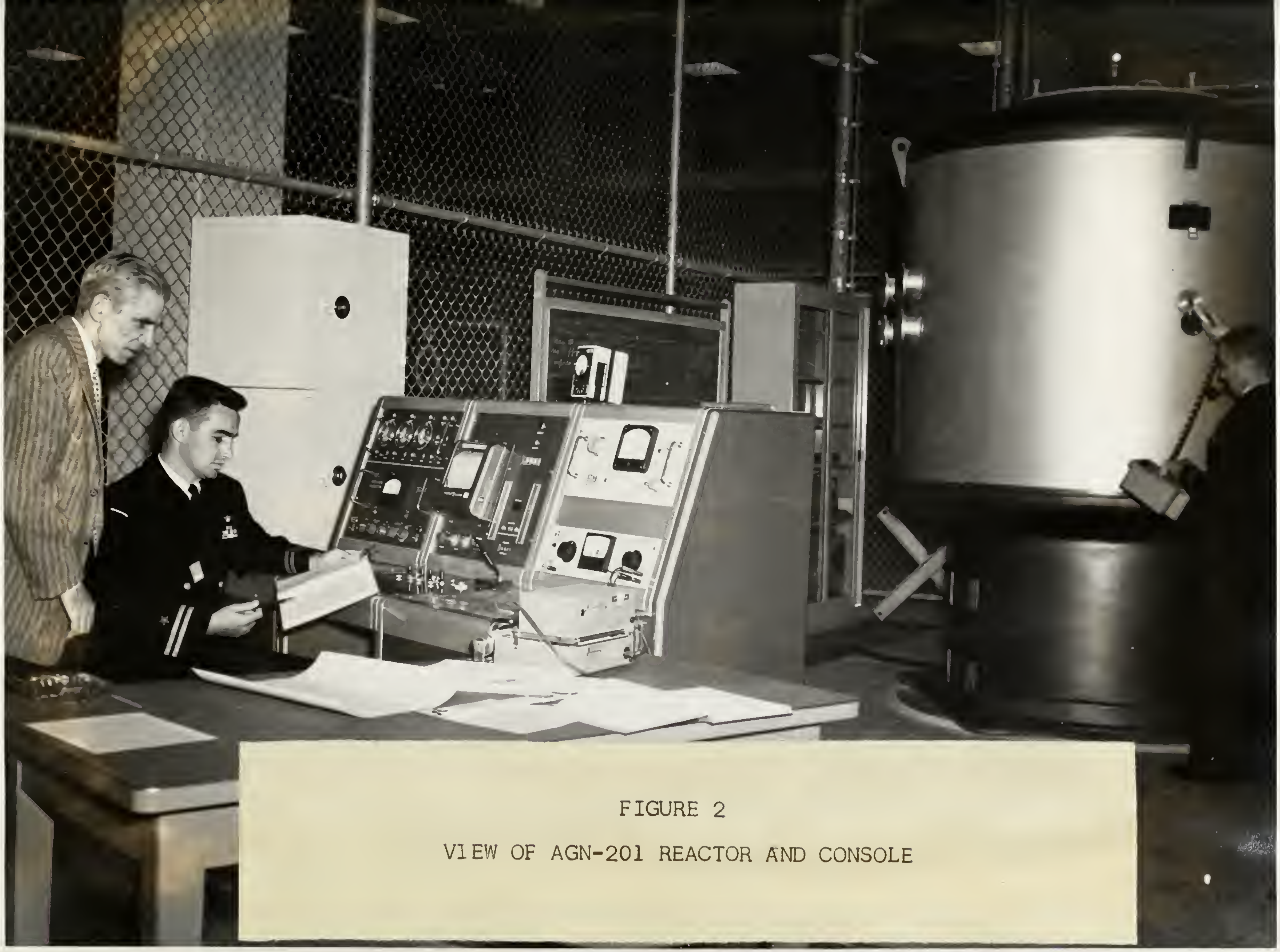


FIGURE 2

VIEW OF AGN-201 REACTOR AND CONSOLE

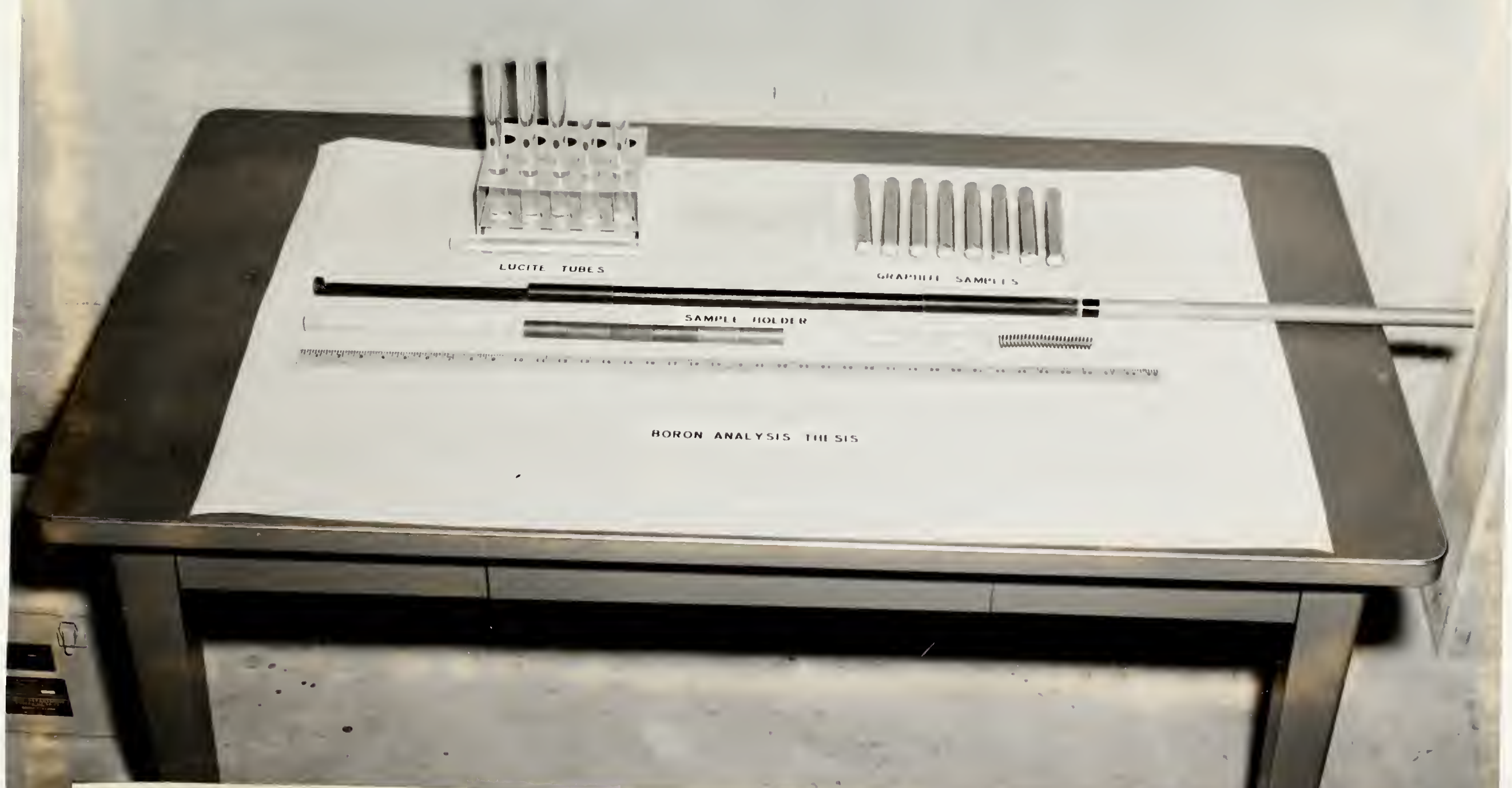
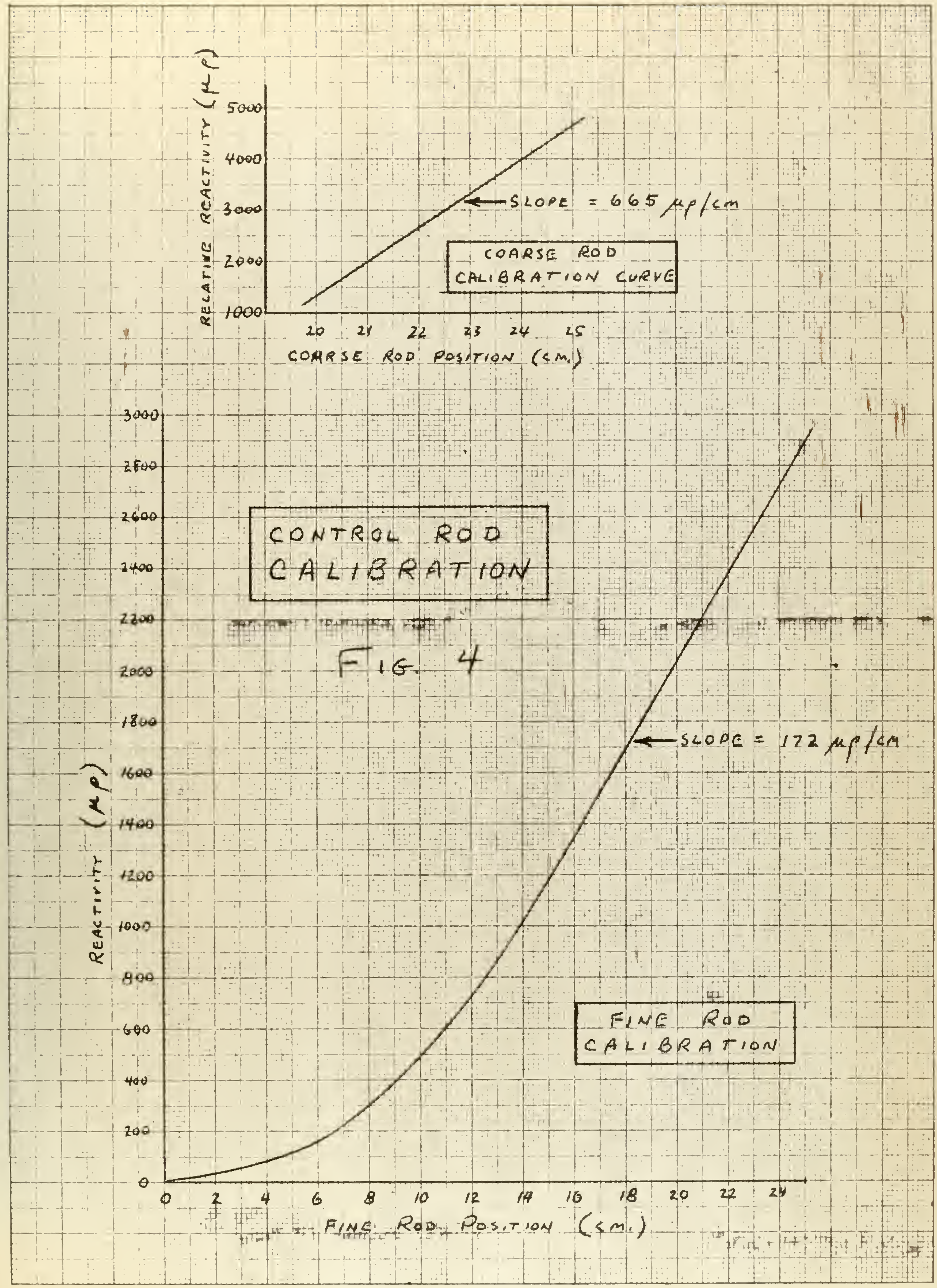


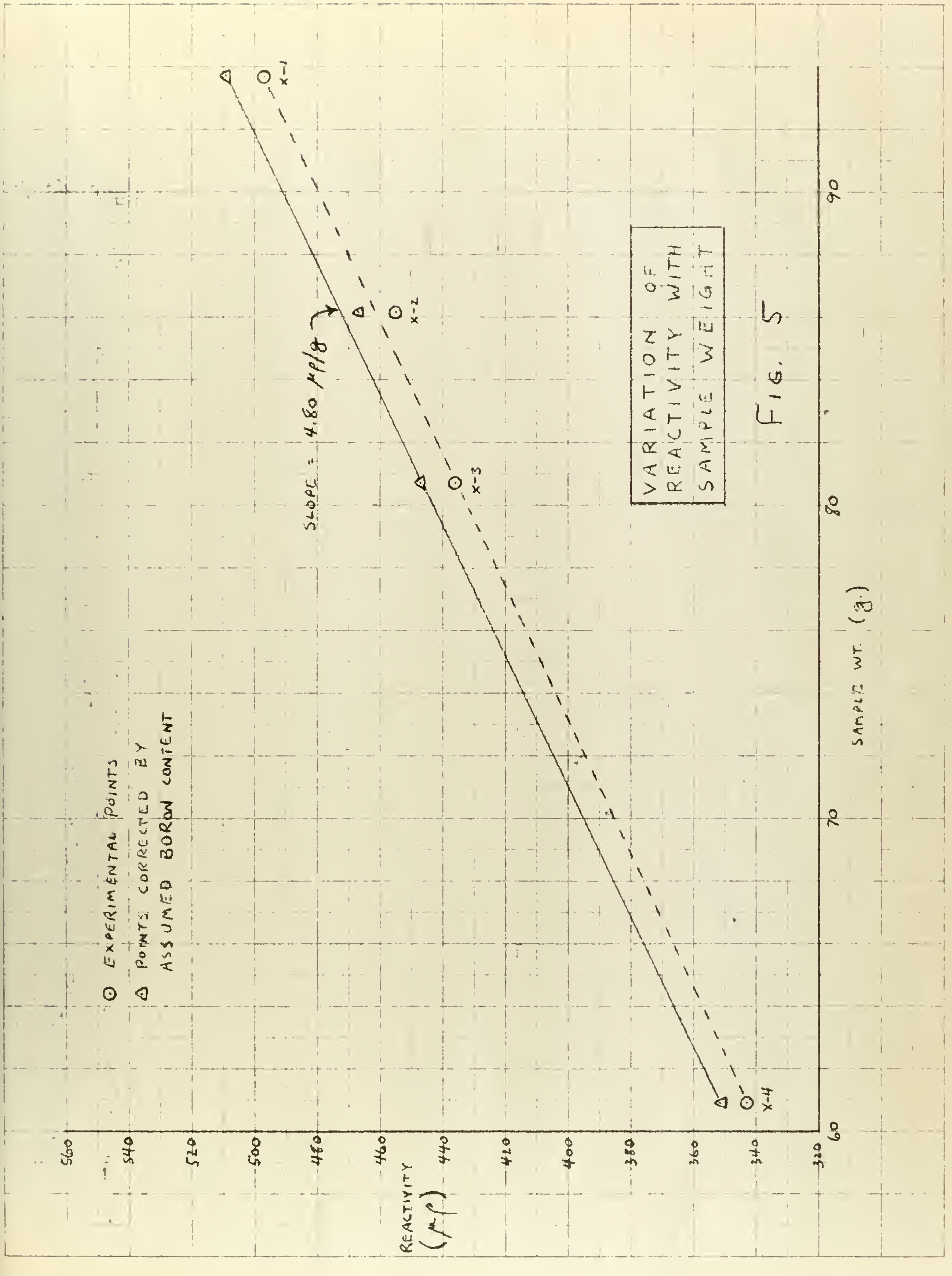
FIGURE 3

EQUIPMENT USED FOR ANALYSIS OF BORON IN GRAPHITE



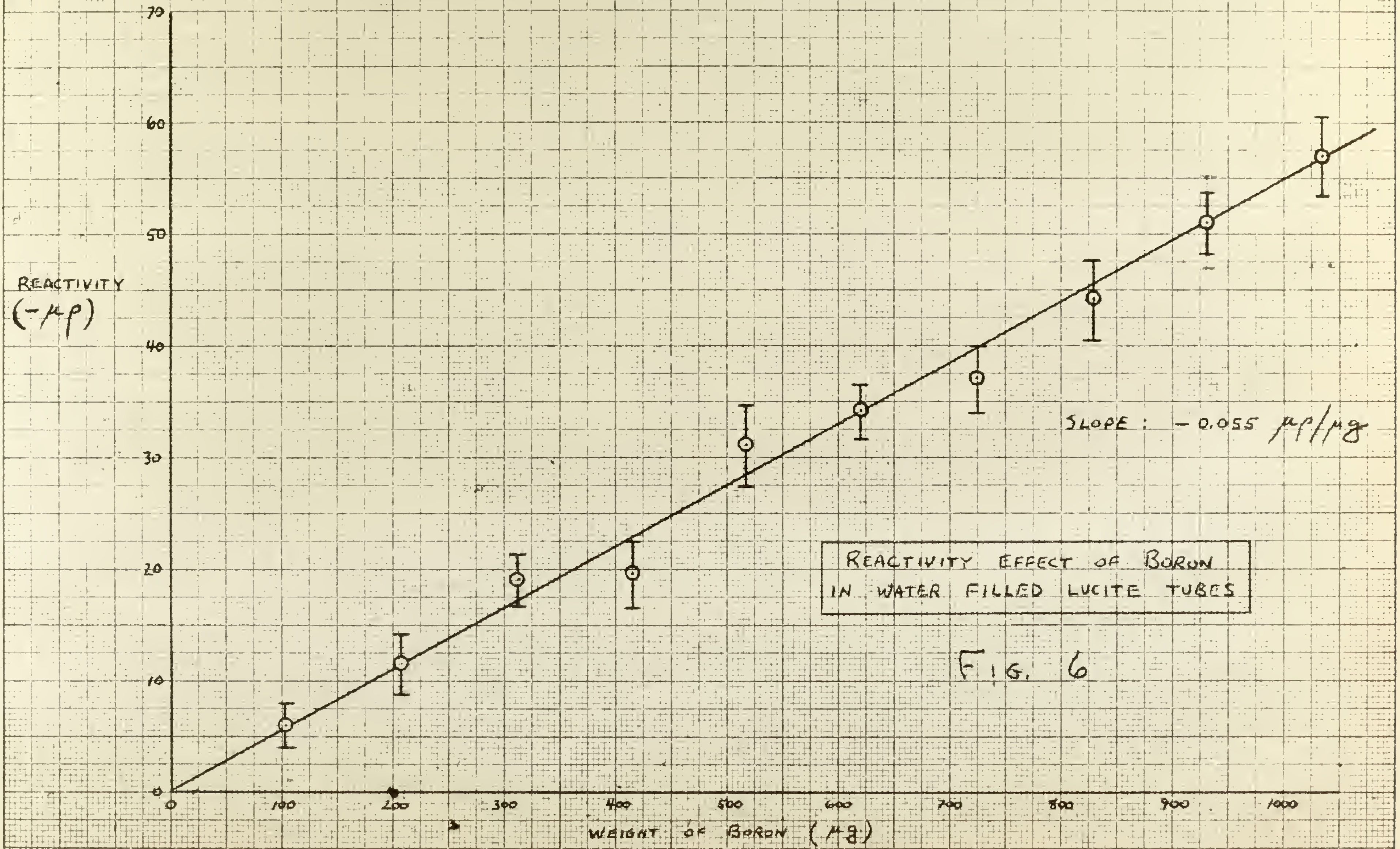
CONTROL ROD CALIBRATION

FIG. 4



VARIATION OF REACTIVITY WITH SAMPLE WEIGHT

FIG. 5



SLOPE : −0.055 μρ/μg

REACTIVITY EFFECT OF BORON
IN WATER FILLED LUCITE TUBES

FIG. 6

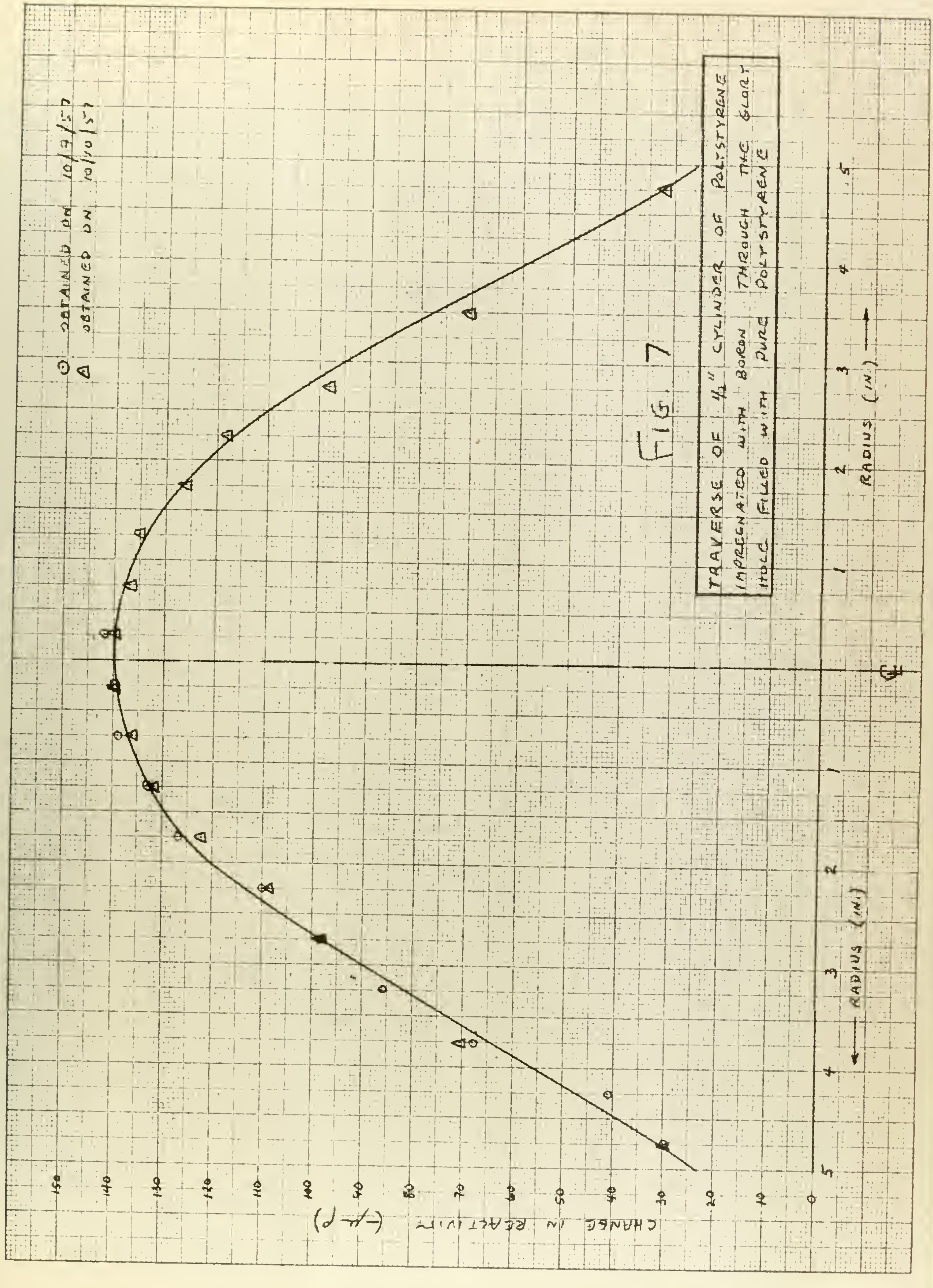


FIG. 7

TRAVERSE OF ½" CYLINDER OF POLYSTYRENE
IMPREGNATED WITH BORON THROUGH THE GLORY
HOLE FILLED WITH PURE POLYSTYRENE

Fig. 7

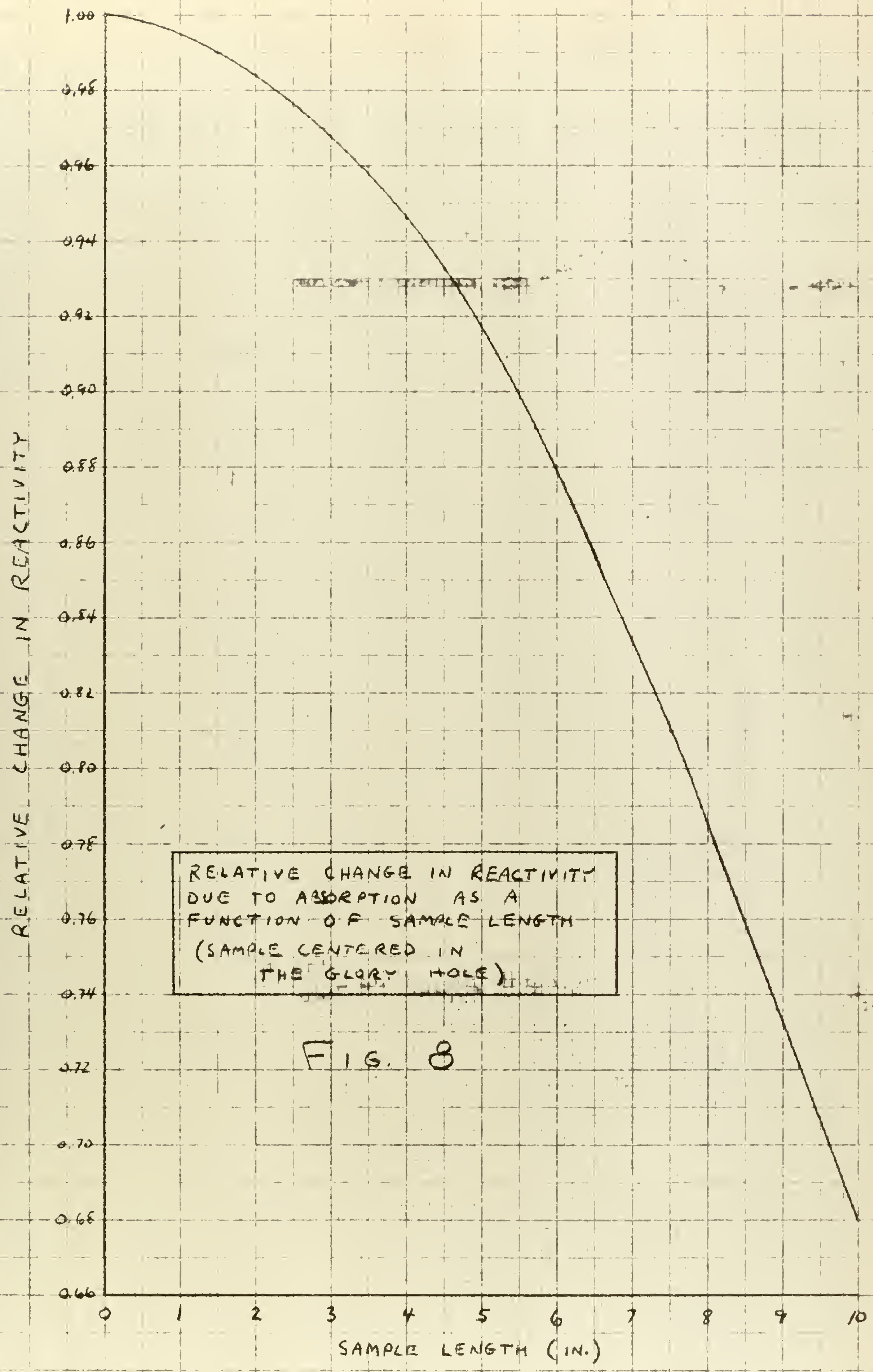
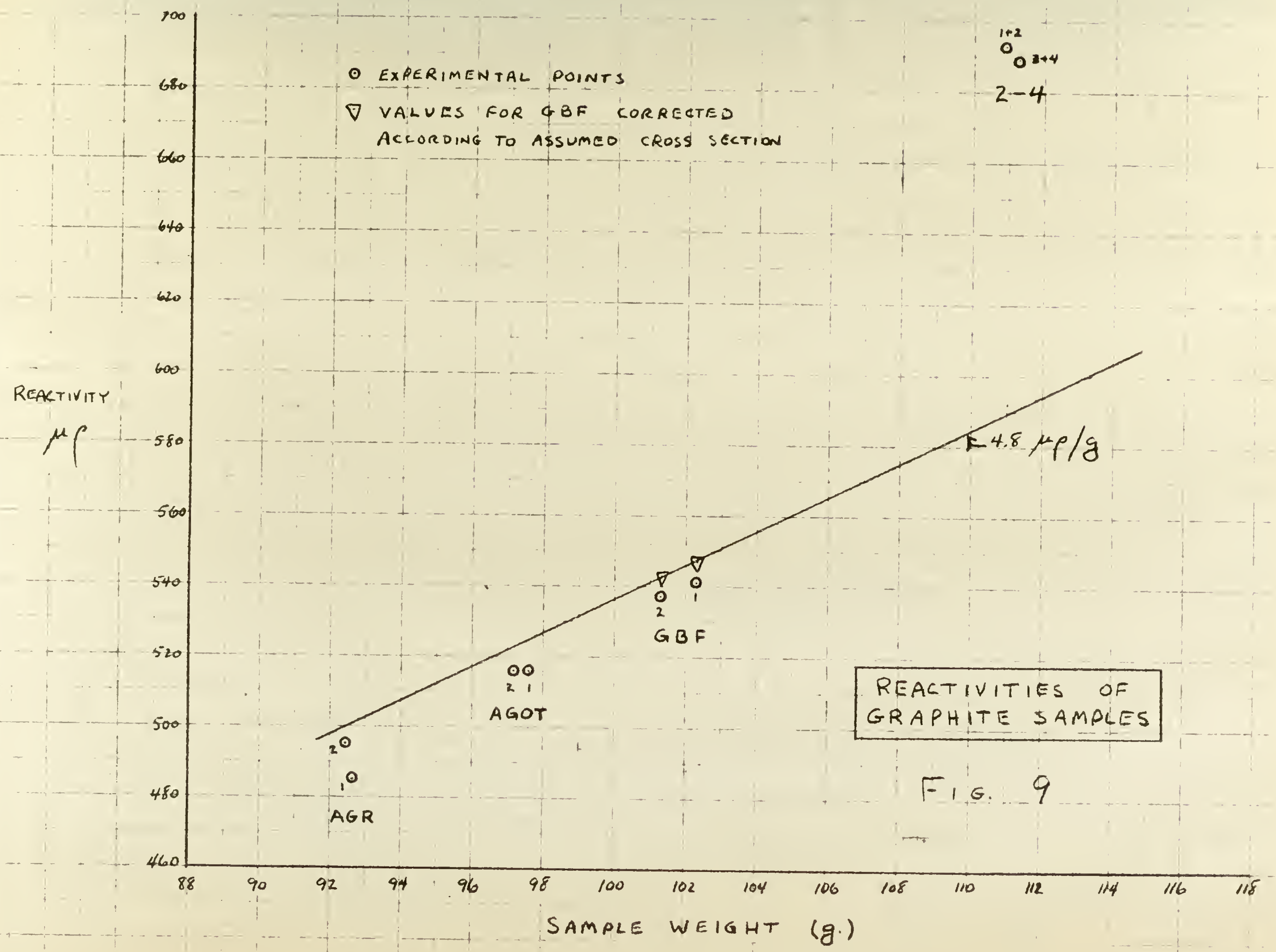

RELATIVE CHANGE IN REACTIVITY
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0.82
0.80
0.78
0.76
0.74
0.72
0.70
0.68
0.66
0
1
2
3
4
5
6
7
8
9
10
SAMPLE LENGTH (IN.)
RELATIVE CHANGE IN REACTIVITY DUE TO ABSORPTION AS A FUNCTION OF SAMPLE LENGTH
(SAMPLE CENTERED IN THE GLORY HOLE)

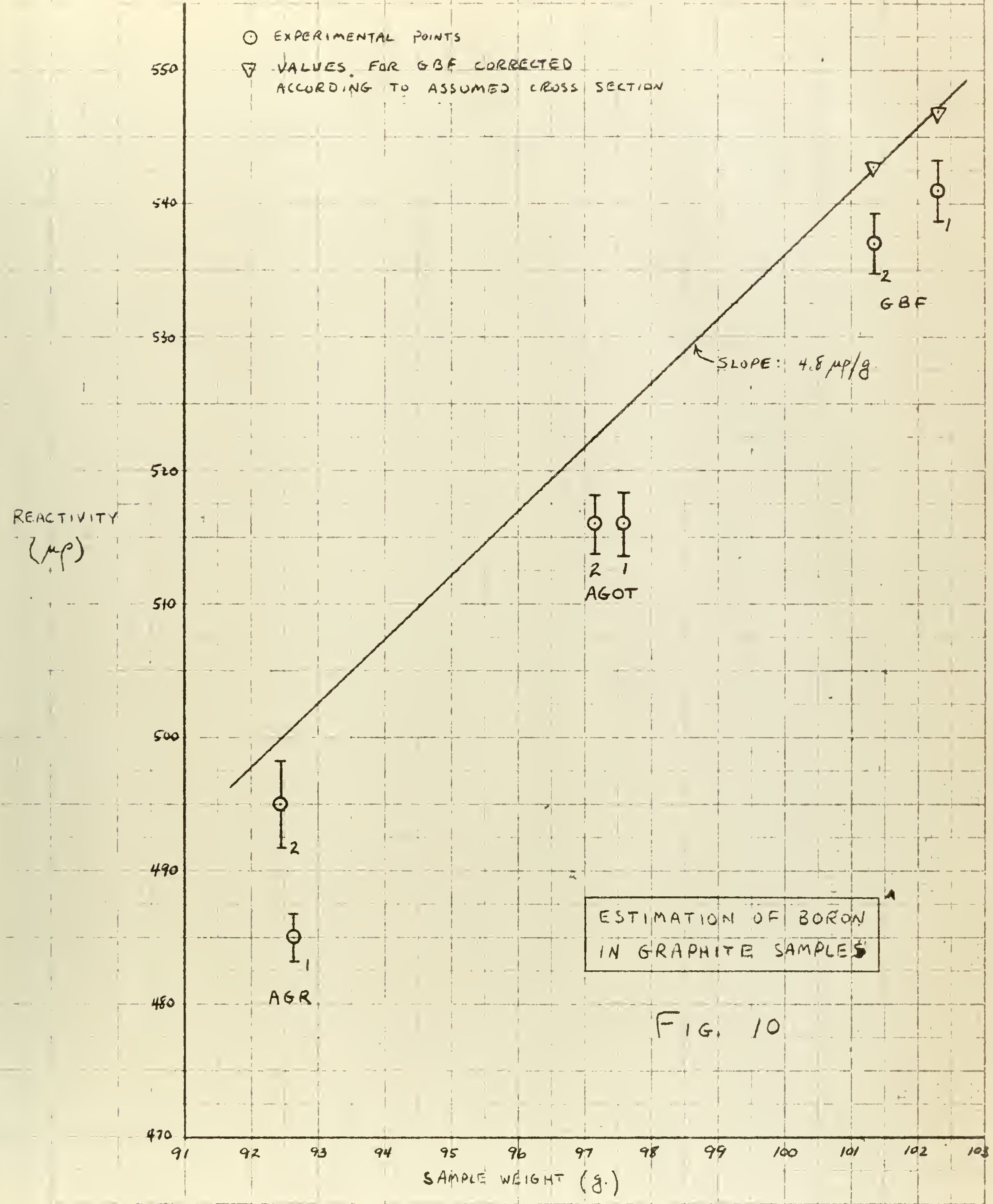
FIG. 8



REACTIVITIES OF GRAPHITE SAMPLES

FIG. 9

Fig. 9



ESTIMATION OF BORON IN GRAPHITE SAMPLES

FIG. 10

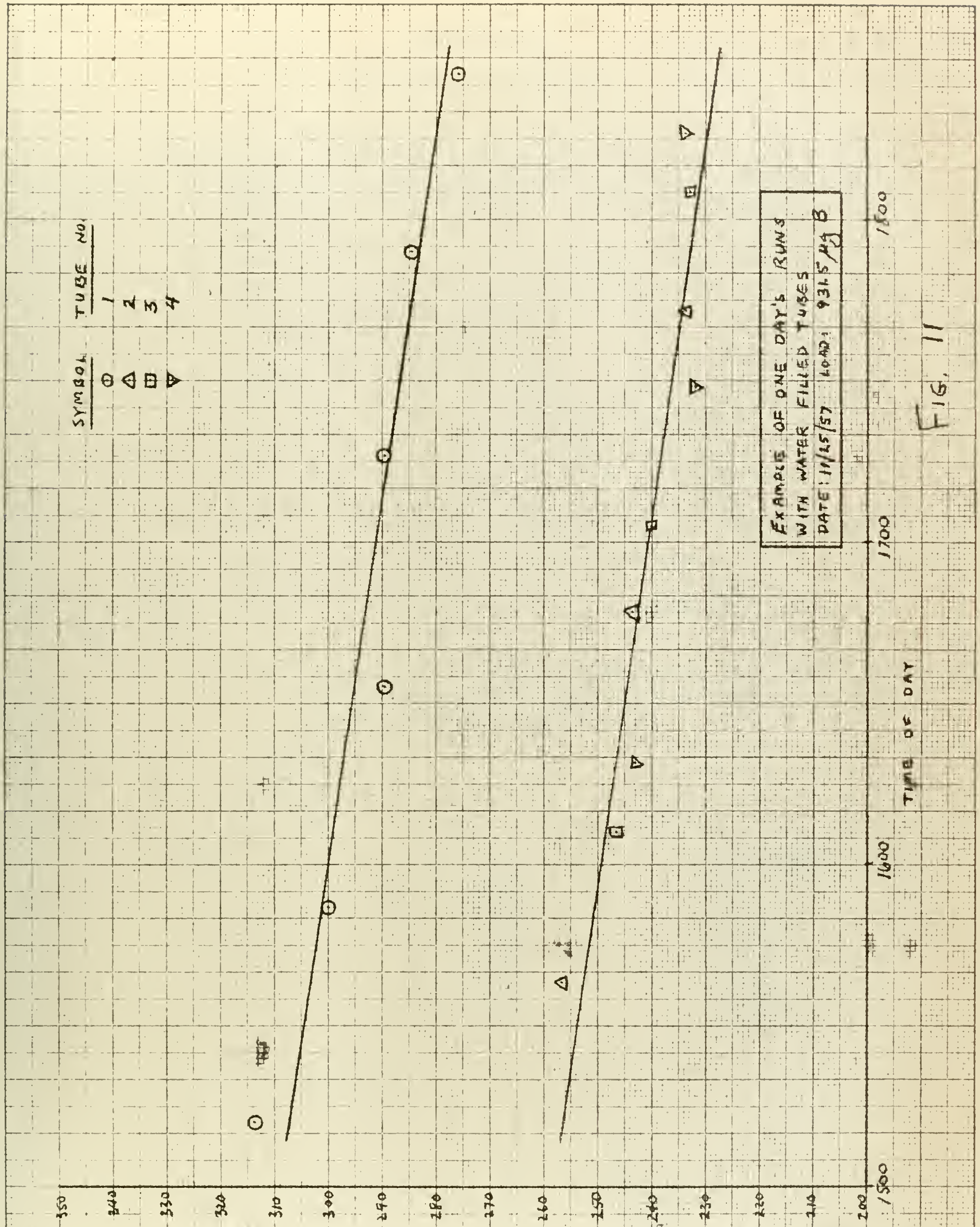

SYMBOL TUBE NO.
⊙ 1
△ 2
⊡ 3
▽ 4
EXAMPLE OF ONE DAY'S RUNS
WITH WATER FILLED TUBES
DATE: 11/25/57 LOAD: 931.5 μg B
RELATIVE
REACTIVITY
μρ
350
340
330
320
310
300
290
280
270
260
250
240
230
220
210
200
1500
1600
1700
1800
TIME OF DAY

FIG. 11

Fig. 11

APPENDIX A

THE INHOUR EQUATION

Reactivity is sometimes expressed in terms of the inverse hour or "inhour" unit, defined as the reactivity which will make the stable reactor period equal to one hour, or 3600 sec.

ρ = reactivity

ℓ = mean lifetime of thermal neutrons

T = stable reactor period

K_{eff} = effective multiplication

γ = mean effectiveness of delayed neutrons

A = the delayed fraction of total fission neutrons

B_i = fraction of delayed neutrons in the ith group

$T_{1/2\,i}$ = half life of the ith group precursor

The following are the values used in computing this equation:

γ = 1.14 (that is, the delayed neutrons are emitted at a lower energy than prompt neutrons and are therefore more effective.)

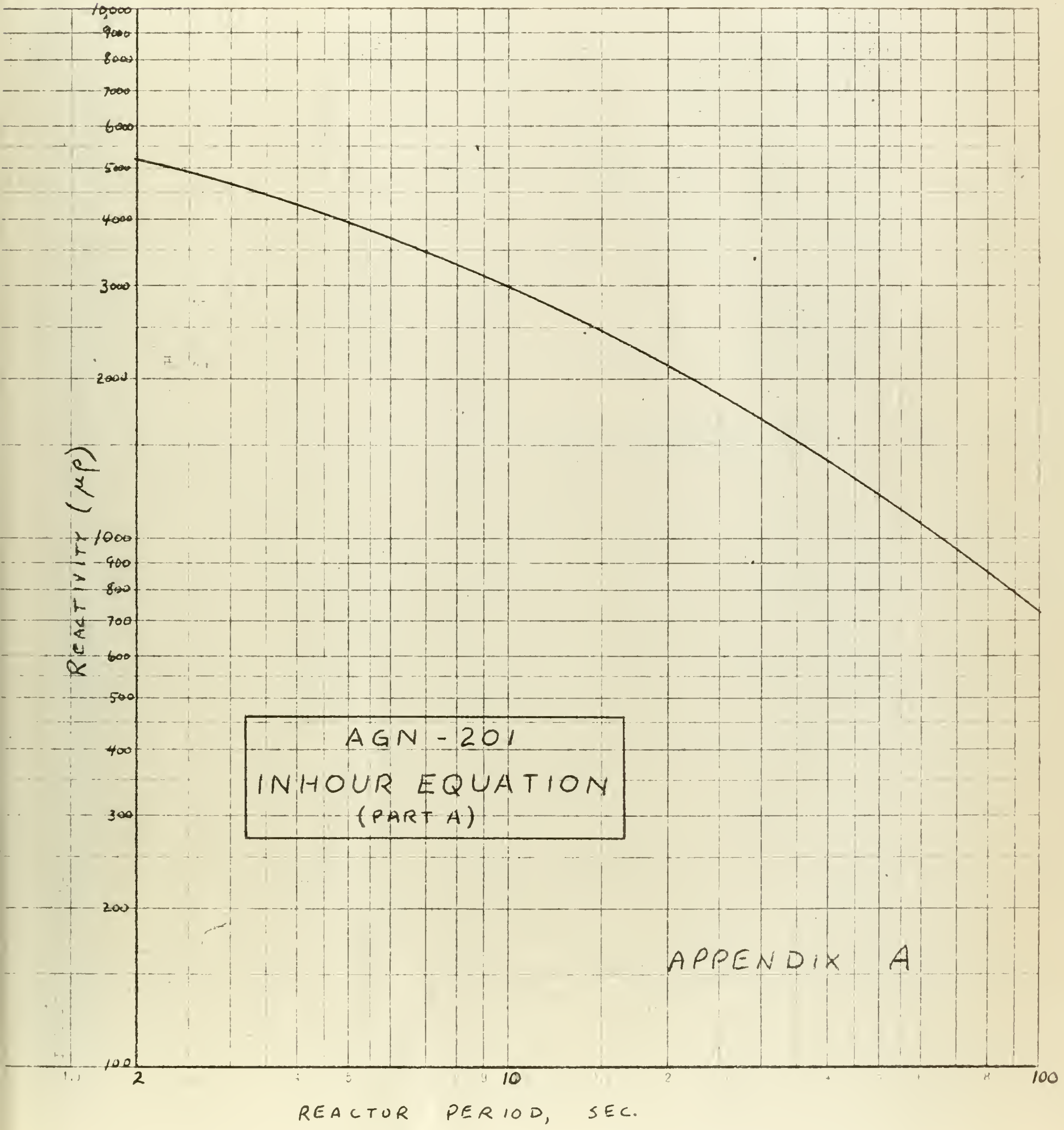
A = 0.00665

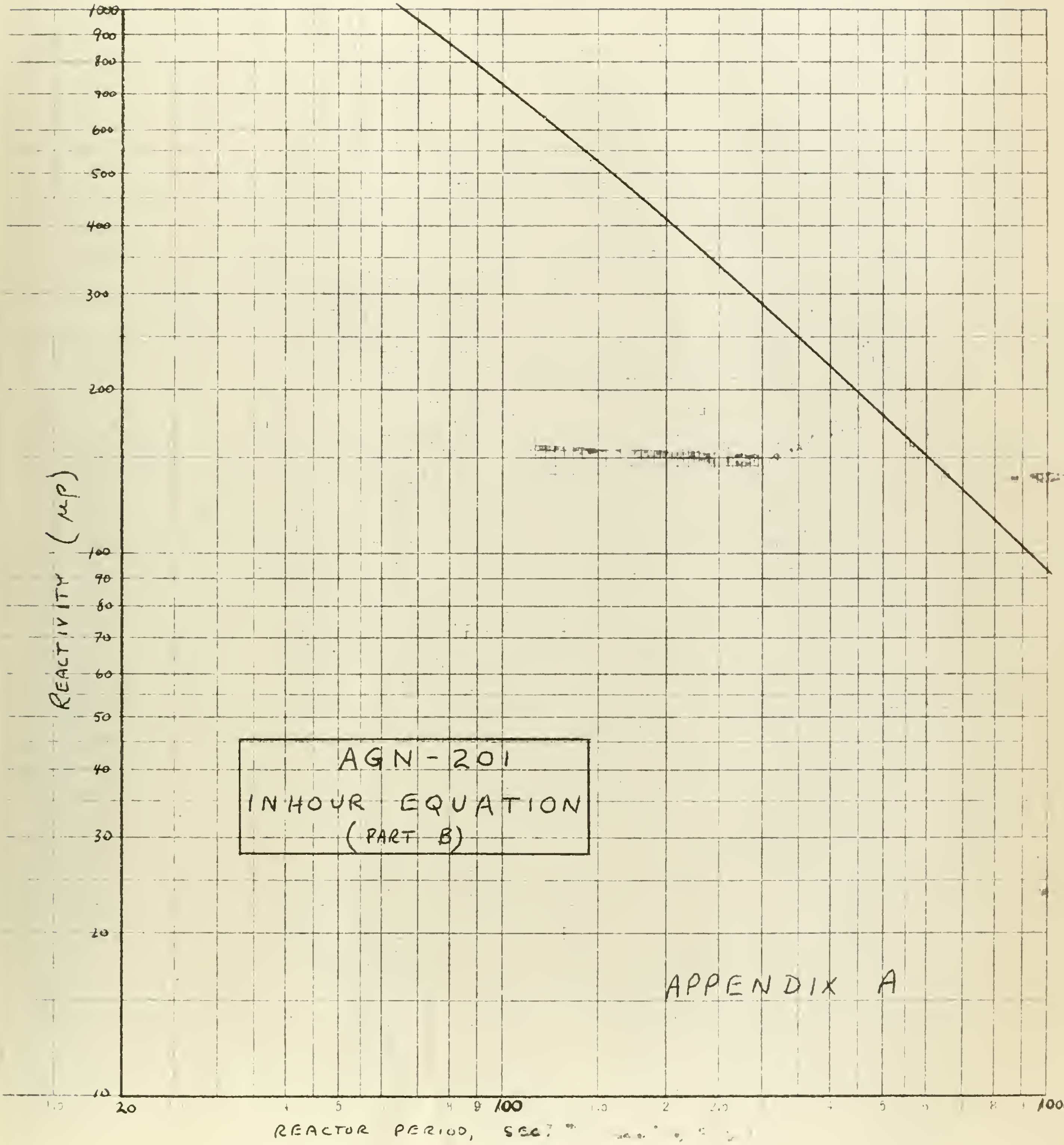
ℓ = 10^{-4} sec.

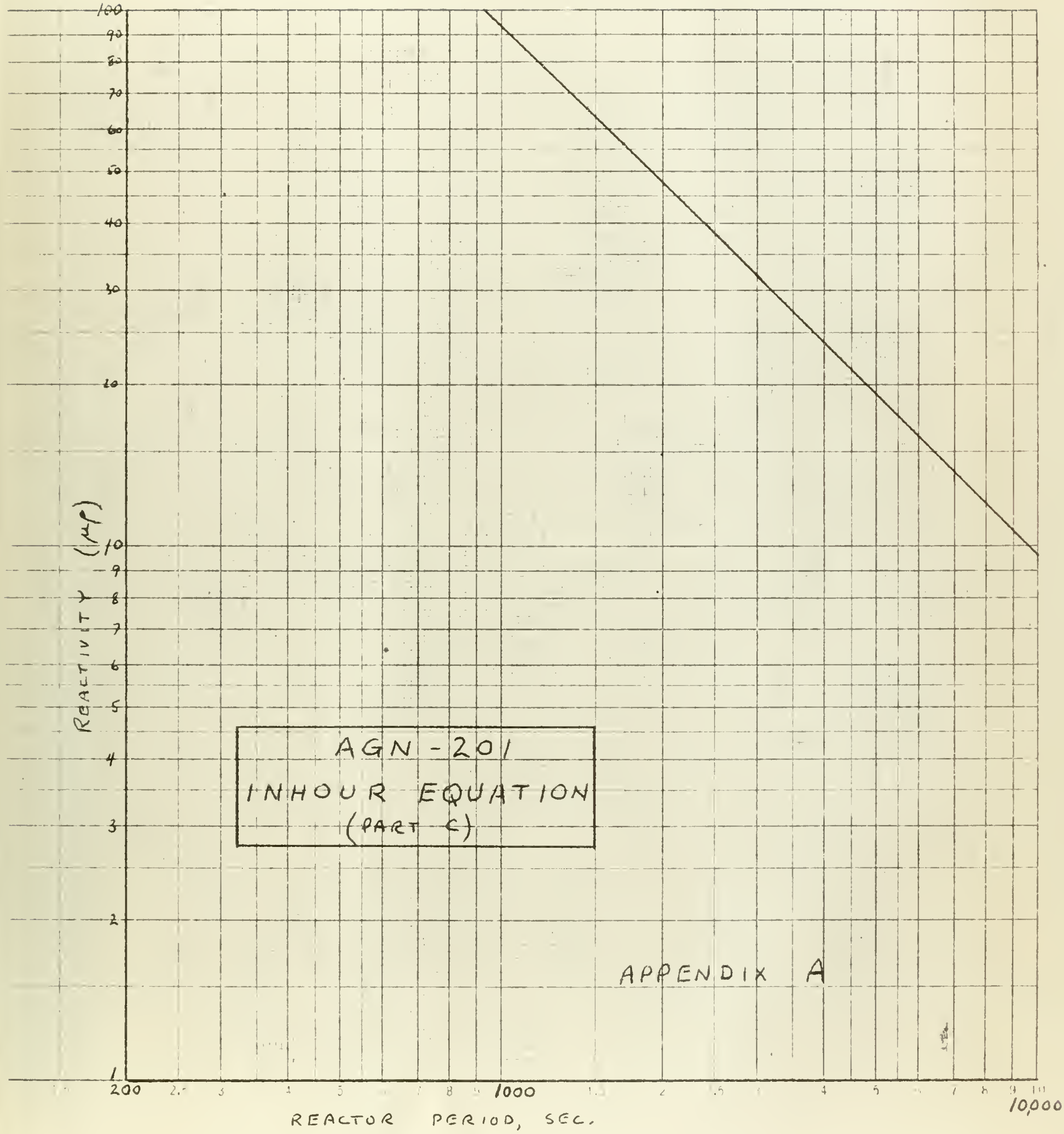
GROUP	B_i	$T_{1/2}$ i (sec)
i = 1	.038	54.51
2	.213	21.84
3	.188	6.00
4	.407	2.23
5	.128	0.496
6	.026	0.179

The inhour equation:

$$\rho = \frac{\ell}{T\,K_{eff}} + \gamma \sum_{i=1}^{6} \frac{A B_i}{1 + \frac{0.693\,T}{T_{1/2\,i}}}$$


10,000
9000
8000
7000
6000
5000
4000
3000
2000
1000
900
800
700
600
500
400
300
200
100
REACTIVITY (μp)
2
5
10
2
100
REACTOR PERIOD, SEC.
AGN - 201
INHOUR EQUATION
(PART A)
APPENDIX A


AGN-201
INHOUR EQUATION
(PART B)
APPENDIX A
REACTIVITY (μρ)
REACTOR PERIOD, SEC.
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
20
5
9
100
2
5
8
1000



AGN - 201
INHOUR EQUATION
(PART C)

APPENDIX A

thesB8017
Estimation of boron impurities in graphi
3 2768 002 07202 7
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